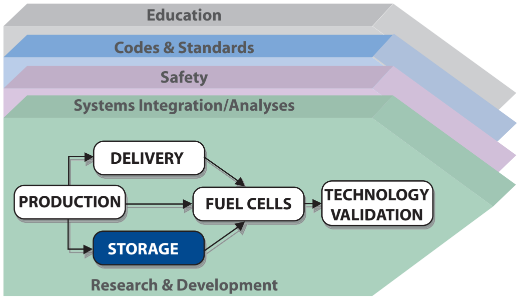
3.3 Hydrogen Storage

Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell power technologies in transportation, stationary, and portable applications. The Hydrogen Storage Program element will focus on the research and development of on-board vehicular hydrogen storage systems that will allow for a driving range of greater than 300 miles. In addition, technologies applicable for off-board storage, such as for refueling infrastructure and Power Parks, will be coordinated with the Hydrogen Delivery Program element.



3.3.1 Technical Goal and Objectives

Goal

Develop and demonstrate viable hydrogen storage technologies for transportation and stationary applications.

Objective

- By 2010, develop and verify on-board hydrogen storage systems achieving 2 kWh/kg (6 wt%), 1.5 kWh/L, and $4/kWh.; by 2015, 3 kWh/kg (9 wt%), 2.7 kWh/L, and $2/kWh.

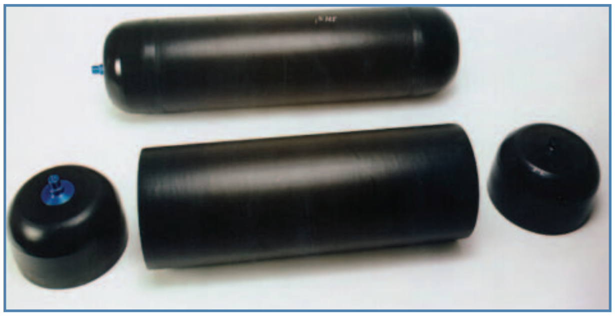
3.3.2 Technical Approach

On-board hydrogen storage to enable a driving range of greater than 300 miles, while meeting vehicular packaging, cost and performance requirements, is the focus of the Hydrogen Storage Program element. Research and development activities for vehicle interface technologies and off-board hydrogen storage will be coordinated with the Hydrogen Delivery Program element—emphasizing that hydrogen delivery entails delivering hydrogen from the point of production to the point of use on-board the vehicle, including storage at the fueling station (see Hydrogen Delivery section 3.2 for complete description of off-board storage).

To lay the strategic foundation for hydrogen storage activities, a series of workshops with scientists and engineers from universities, national laboratories and industry was held to identify R&D priorities. A "Think Tank" meeting, which included Nobel laureates and other award-winning scientists, was held to identify advanced material concepts and to develop an R&D strategy. Interactions with the DOE Office of Science are ongoing to define and coordinate the basic research activities for hydrogen storage materials.

Gravimetric, volumetric and cost targets for hydrogen storage have been developed for 2010 and 2015, as indicated in the objectives. Storage approaches currently being pursued are: 1) advanced concepts, conformability and cost reduction of compressed gas and cryogenic hydrogen tanks for near-term vehicles, and 2) reversible solid-state hydrogen storage materials, chemical hydrogen storage, and new materials and concepts for the longer-term vehicle applications (see Figures 3.3.1 and 3.3.2). The primary focus is on the latter set of technologies and on exploratory research with potential to meet long-term goals, rather than on pre-commercial technology development such as high-pressure tanks. Currently, hydrogen is stored both off-board and on-board prototype vehicles as a high-pressure compressed gas or as a cryogenic liquid. Compressed hydrogen gas tanks will likely be used in early hydrogen-powered vehicles and will need to meet cost and packaging requirements to play a role in the transition to the hydrogen economy. Furthermore, tanks will be required for all future storage approaches (e.g. solid-state or liquid chemical approaches) and will need to conform to space limitations as well as meet performance requirements such as heat management during fueling. Hence, current efforts in tank R&D also include novel concepts that are applicable to multiple forms of storage.

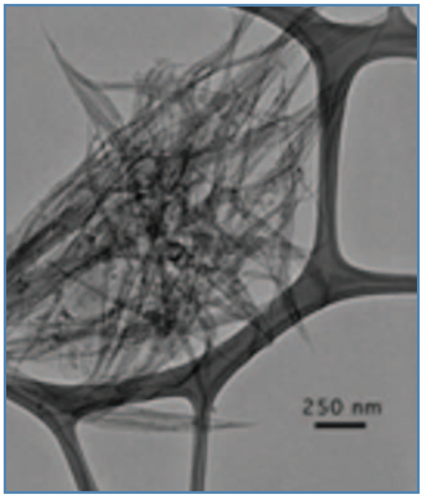
Figure 3.3.1. Hydrogen storage tanks.



The Hydrogen Storage Program element will include on-going analysis to examine the lifecycle cost, energy efficiency, and environmental impact of the technologies developed, any changes in the system-level requirements that might alter the technical targets, and the progress of each technology development effort toward achieving the technical targets.

As technologies are down-selected with potential for on-board storage, future activities on vehicle interface technologies will be coordinated with the Delivery Program element. Vehicle refueling connection devices will need to be compatible with high pressure and cryogenic storage in the near-term. In the long term, as progress is made on solid-state or liquid-based options, vehicle refueling issues such as thermal management or byproduct reclamation will need to be addressed.

Figure 3.3.2. Micrograph of carbon nanostructure for hydrogen storage.



Funding for hydrogen storage R&D will be scaled down according to measurable progress—as technical and cost targets are met or missed, funding for particular technological approaches will be adjusted. When all performance, safety and cost targets are met, hydrogen storage R&D funding will end as appropriate. If specific performance issues remain at that time, R&D could be extended if the risk of the continued effort is justified by the potential benefit.

3.3.3 Programmatic Status

Current Activities

Table 3.3.1 summarizes the current (FY 2004) activities in the Hydrogen Storage Program element. For compressed hydrogen, lightweight composite tanks with high-pressure ratings and conformability are being developed. Complex metal hydrides, including alanates and other promising materials, are being explored to determine their potential for hydrogen storage and to improve our understanding of hydrogen storage processes. The search for new metal hydrides also includes combinatorial and high-throughput materials development and screening. Similarly, carbon nanotubes and other carbon-based materials are being investigated to explore possible novel hydrogen uptake mechanisms. Projects on chemical hydrogen storage, such as sodium borohydride and magnesium hydride slurries, were initiated in FY 2004, with a focus on the key issue for chemical hydrogen storage—off-board regeneration of the spent fuel. A project was also initiated on off-board hydrogen storage and will be coordinated with the Delivery Program element (see section 3.2). Also shown below are the new awards on novel materials and concepts that were announced in FY 2004. New projects on systems analysis will include performance, cost and life-cycle analyses of on-board storage options. Finally, a test and evaluation facility is being established to develop standard test protocols and provide independent verification of hydrogen storage performance in reversible solid-state materials.

In FY 2005, coordinated activities will be launched with multiple university, industry and national laboratory partners in the key focus areas of metal hydrides, carbon-based materials and chemical hydrogen storage. New materials and concepts will be an emphasis in the FY05 storage portfolio. Future efforts also include collaboration with the DOE Office of Science in FY 2005 on basic science, theory and modeling related to various hydrogen storage technologies.

Table 3.3.1. Current Hydrogen Storage Activities

Approach	Organizations	Project Focus
Compressed Hydrogen Tanks	Quantum	10,000 psi Composite Tanks, Cost Reduction
	Lawrence Livermore National Laboratory	Cryo-compressed Tanks and Advanced Concepts
Complex Metal Hydrides	United Technologies Research Center (2 projects)	Materials discovery of new alanate compositions; study of system prototype using sodium alanate
	United Oil Products (UOP)	Discovery of novel complex hydrides using combinatorial methods
	Center of Excellence on Metal Hydrides (Sandia National Laboratory-Livermore, Brookhaven National Laboratory, California Institute of Technology, General Electric, HRL Laboratories, Intematix Corporation, Jet Propulsion Laboratory, NIST, Oak Ridge National Laboratory, Savannah River National Laboratory, Stanford University, University of Hawaii, University of Illinois-Urbana-Champaign, University of Nevada-Reno, University of Pittsburgh/Carnegie Mellon University, University of Utah)	Light-weight complex hydrides, destabilized binary hydrides, intermetallic hydrides, modified lithium amides, and other on-board reversible hydrides
Carbon	Center of Excellence on Carbon-based Materials (National Renewable Energy Laboratory, Air Products & Chemicals, Inc., California Institute of Technology, Duke University, Lawrence Livermore National Laboratory, NIST, Oak Ridge National Laboratory, Penn State University, Rice University, University of Michigan, University of North Carolina, University of Pennsylvania)	Carbon-based materials and high surface area sorbents; storage capacity, mechanisms, characterization, optimization
Chemical Hydrides	Millennium Cell	Sodium borate regeneration
	Air Products & Chemicals, Inc.	Liquid chemical hydride
	Safe Hydrogen LLC	Magnesium hydride slurry
	Center of Excellence on Chemical Hydrogen Storage (Los Alamos National Laboratory, Pacific Northwest National Laboratory, Intematix, Millennium Cell, Northern Arizona University, Penn State University, Rohm and Haas, University of Alabama, UC-Davis, UCLA, University of Pennsylvania, University of Washington, US Borax)	New chemical hydrogen storage and regeneration processes

New Materials and Concepts	Cleveland State University	Complex metal nanostructured grids
	Alfred University	Hollow glass microspheres and electromagnetic radiation
	Carnegie Institute of Washington	Clathrates
	Gas Technology Institute	Graphite-based materials
	Michigan Technological University	Metal perhydrides
	Research Triangle Institute	Nitrogen/boron hydrides
	SUNY -Syracuse	Novel nanostructured activated carbon materials
	TOFTEC, Inc.	Synthesis of carbon and boron nitride materials by gamma irradiation
	University of California-Berkeley and Lawrence Berkeley National Laboratory	Nanoporous polymers, nanoporous coordination solids, destabilized high-density hydrides, nanostructured boron nitride and magnesium and metal alloy nanocrystals
	University of California-Santa Barbara	Nanoporous nickel phosphates, inorganic and organic framework materials and metal hydrogen complexes
	University of Connecticut	Mechanically activated, nanoscale lithium nitride materials
	University of Michigan	Metal-organic frameworks
	University of Missouri	Organic clathrates
	University of Pennsylvania and Drexel University	Carbide based nanomaterials
Testing and Evaluation	Southwest Research Institute	Standard Test Protocols, Independent Test Facility
Analysis	TIAX LCC	Analysis of performance and life cycle costs of on-board storage options
	Argonne National Laboratory	Analysis of hybrid concepts and systems

Technology Status (Demonstrations)

In the area of on-board hydrogen storage, the state-of-the-art is 5,000- and 10,000-psi compressed tanks, and cryogenic liquid hydrogen tanks. Tanks have been certified worldwide according to ISO 11439 (Europe), NGV2 (U.S.), and Reijikijun Betten (Iceland) standards, and approved by TUV (Germany) and KHK (Japan). They have been demonstrated in several prototype fuel cell vehicles and are commercially available at low production volumes. All-composite 10,000-psi tanks have demonstrated a 2.35 safety factor (23,500-psi burst pressure) as required by the European Integrated Hydrogen Project specifications. Liquid hydrogen tanks have also been demonstrated. A sodium borohydride system has been demonstrated in a concept vehicle. A lithium hydride slurry prototype has been demonstrated in a pick up truck with a hydrogen internal combustion engine.

3.3.4 Technical Challenges

For transportation applications, the overarching technical challenge for hydrogen storage is how to store the necessary amount of hydrogen fuel required for conventional driving range (>300 miles), within the constraints of weight, volume, durability, efficiency and total cost. Clearly, many important technical challenges for hydrogen storage must be resolved to meet the ultimate performance and safety targets. Substantial improvements must be made in the weight, volume and cost of these systems, for vehicular applications. Durability over the performance lifetime of these systems must be verified and validated, and acceptable refueling times must be achieved. Section 3.3.4.1 lists specific technical targets that the hydrogen storage system must achieve to meet customer-driven requirements for vehicle performance. Section 3.3.4.2 lists the specific technical barriers that must be overcome to achieve the performance targets. Section 3.3.5 describes the tasks that will be carried out to resolve the identified technical barriers.

3.3.4.1 Technical Targets

The technical performance targets for hydrogen storage systems are summarized in Table 3.3.2. Figure 3.3.3 shows the status of current technologies relative to performance and cost targets. These targets were established through the FreedomCAR and Fuel Partnership between DOE, the U.S. Council for Automotive Research (USCAR) and the energy companies. The targets are subject to change as more is learned about system-level requirements and as fuel cell technology progresses.

Based on the lower heating value (LHV) of hydrogen and greater than 300-mile vehicle range, the targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components. The targets are based on the U.S. weighted average corporate vehicle (WACV) that includes minivans, light trucks, economy cars, and SUV/crossover vehicles, in proportion to their sales. A detailed explanation of each target is provided at www.eere.energy.gov/hydrogenandfuelcells. It should also be noted that unless otherwise indicated in Table 3.3.2, the targets are for both internal combustion engine and fuel cell power plants.

In addition, hydrogen storage systems must be energy efficient in delivering hydrogen to the vehicle power plant. For on-board reversible systems, greater than 90% energy efficiency for the energy delivered to the power plant from the on-board storage system is required. For systems regenerated off-board, the overall efficiency is also important. In this case, the energy content of the hydrogen delivered to the automotive power plant should be greater than 60% of the total energy input to the process, including the input energy of hydrogen and any other fuel streams for generating process heat and electrical energy. This is based on the DOE on-board target of 90% efficiency and the DOE off-board energy efficiency targets of 79% for hydrogen produced from natural gas and 85% for well-to-tank efficiency.

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Table 3.3.2. Technical Targets: On-Board Hydrogen Storage Systems

Storage Parameter	Units	2007[a]	2010	2015
Usable, specific-energy from H_2 (net useful energy/max system mass)[b] ("Gravimetric Capacity")	kW·h/kg ($kg\ H_2/kg$)	1.5 (0.045)	2 (0.06)	3 (0.09)
Usable energy density from H_2 (net useful energy/max system volume) ("Volumetric Capacity")	kW·h/L ($kg\ H_2/L$)	1.2 (0.036)	1.5 (0.045)	2.7 (0.081)
Storage system cost[c]	$/kW·h net ($/kg H_2)	6 (200)	4 (133)	2 (67)
Fuel cost[d]	$ per gallon gasoline equivalent at pump	3	1.5	1.5
Operating ambient temperature[e]	°C	-20/50 (sun)	-30/50 (sun)	-40/60 (sun)
Cycle life (1/4 tank to full)[f]	Cycles	500	1000	1500
Cycle life variation[g]	% of mean (min) @ % confidence	N/A	90/90	99/90
Minimum and Maximum delivery temperature of H_2 from tank	°C	-20/85	-30/85	-40/85
Minimum full-flow rate	(g/s)/kW	0.02	0.02	0.02
Minimum delivery pressure of H_2 from tank; FC=fuel cell, ICE=internal combustion engine	Atm (abs)	8 FC 10 ICE	4 FC 35 ICE	3 FC 35 ICE
Maximum delivery pressure of H_2 from tank[h]	Atm (abs)	100	100	100
Transient response 10%-90% and 90%-0%[i]	s	1.75	0.75	0.5
Start time to full-flow at 20°C[j]	s	4	4	0.5
Start time to full-flow at minimum ambient[j]	s	8	8	2
System Fill Time	min	10	3	2.5
Loss of useable hydrogen[k]	(g/h)/kg H_2 stored	1	0.1	0.05
Quality[l] (H_2 from storage system)	%	98% (dry basis)		
Permeation and leakage[m]	Scc/h	Federal enclosed-area safety-standard		
Toxicity		Meets or exceeds applicable standards		
Safety		Meets or exceeds applicable standards		

Useful constants: 0.2778kWh/MJ, ~33.3kWh/gal gasoline equivalent.

[a] Some near-term targets have been achieved with compressed and liquid tanks. Emphasis is on materials-based technologies.

[b] Generally the 'full' mass (including hydrogen) is used, for systems that gain weight, the highest mass during discharge is used.

[c] 2003 US$; total cost includes any component replacement if needed over 15 years or 150,000 mile life.

[d] 2001 US$; includes off-board costs such as liquefaction, compression, regeneration, etc; 2015 target based on H_2 production cost of $1.50/gasoline gallon equivalent untaxed (subject to change based on DOE hydrogen production cost target).

[e] Stated ambient temperature plus full solar load. No allowable performance degradation from –20C to 40C. Allowable degradation outside these limits is TBD.

[f] Equivalent to 100,000; 200,000; and 300,000 miles respectively (current gasoline tank spec).

[g] All targets must be achieved at end of life.

[h] In the near term, the forecourt should be capable of delivering 10,000 psi compressed hydrogen, liquid hydrogen, or chilled hydrogen (77 K) at 5,000 psi. In the long term, it is anticipated that delivery pressures will be reduced to between 50 and 150 atm for solid state storage systems, based on today's knowledge of sodium alanates.

[i] At operating temperature.

[j] Flow must initiate within 25% of target time.

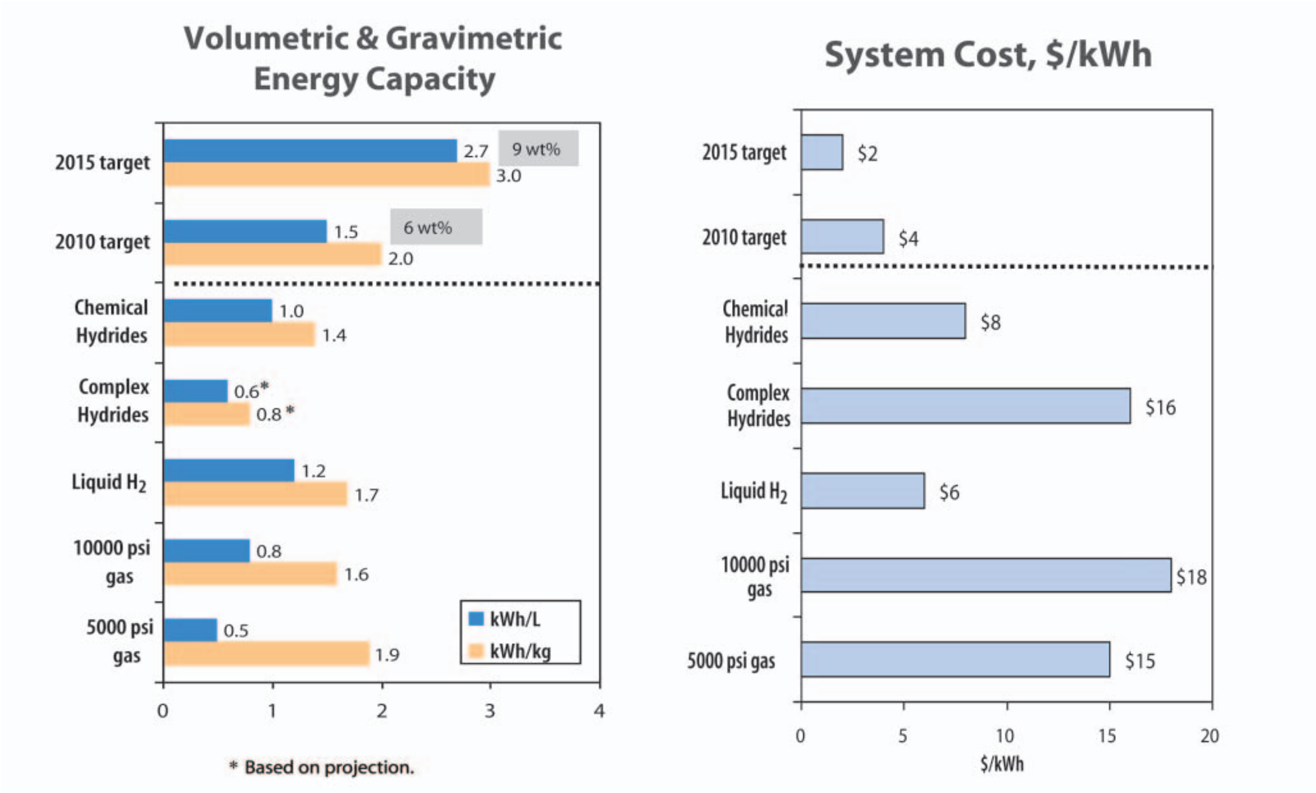
[k] Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of range.

[l] For fuel cell systems, steady state levels less than 10 ppb sulfur, 1 ppm carbon monoxide, 100 ppm carbon dioxide, 1 ppm ammonia, 100 ppm non-methane hydrocarbons on a C-1 basis; oxygen, nitrogen and argon can't exceed 2%. Particulate levels must meet ISO standard 14687. Some storage technologies may produce contaminants for which effects are unknown; these will be addressed as more information becomes available.

[m] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with CSA/NGV2 standards for vehicular tanks. This includes any coating or enclosure that incorporates the envelope of the storage system.

The current status for system capacity and cost, as shown in Figure 3.3.3, are estimates provided by technology developers and the R&D community. All targets must be achieved simultaneously; however, status is not neccessarily reported from a single system. Because it is challenging to estimate *system-level* weights and volumes when research is still at the stage of materials development, the current status data will be revisited and updated periodically. However, it is clear that none of the current systems meets the combined gravimetric, volumetric, and system cost targets for either 2010 or 2015. Also note that although recent accomplishments may show materials-based capacities as high as 5 wt%, the targets of 6 wt% by 2010 and 9 wt% by 2015 are *system-level* capacities that include the material, tank and all balance-of-plant components of the storage system. The system-level data also needs to include the first charge of hydrogen as well as any preconditioning such as purification, liquefaction and regeneration of material, particularly for chemical hydrogen storage, for which the cost of regenerating spent fuel will need to be included.

Figure 3.3.3 Status of current technologies relative to the key performance and cost targets.



3.3.4.2 On-Board Hydrogen Storage Technical Barriers

General

A. Cost. The cost of on-board hydrogen storage systems is too high, particularly in comparison with conventional storage systems for petroleum fuels. Low-cost materials and components for hydrogen storage systems are needed, as well as low-cost, high-volume manufacturing methods.

B. Weight and Volume. The weight and volume of hydrogen storage systems are presently too high, resulting in inadequate vehicle range compared to conventional petroleum fueled vehicles. Materials and components are needed that allow compact, lightweight, hydrogen storage systems while enabling greater than 300-mile range in all light-duty vehicle platforms. Reducing weight and volume of thermal management components is required.

C. Efficiency. Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to get hydrogen in and out of the material is an issue for reversible solid-state materials. Life-cycle energy efficiency may be a challenge for chemical hydrogen storage technologies in which the spent medium and by-products are typically regenerated off-board. In addition, the energy associated with compression and liquefaction must be considered for compressed and liquid hydrogen technologies. Thermal management for charging and releasing hydrogen from the storage system needs to be optimized to increase overall efficiency.

D. Durability. Durability of hydrogen storage systems is inadequate. Materials and components are needed that allow hydrogen storage systems with a lifetime of 1500 cycles and tolerance to fuel contaminants.

E. Refueling Time. Refueling times are too long. There is a need to develop hydrogen storage systems with refueling times of less than three minutes, over the lifetime of the system. Thermal management during refueling is a critical issue that must be addressed.

F. Codes and Standards. Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and assure safety and public acceptance, have not been established. Standardized hardware and operating procedures, and applicable codes and standards, are required.

G. System Life-Cycle Assessments. Assessments of the full life cycle, cost, efficiency, and environmental impact for hydrogen storage systems are lacking.

Compressed Gas Systems

H. Sufficient Fuel Storage for Acceptable Vehicle Range. Compressed hydrogen storage systems that contain enough hydrogen to provide equivalent range to conventional vehicles are too bulky, which compromises passenger and luggage space.

I. Materials. High-pressure containment limits the choice of construction materials and fabrication techniques, within the weight, volume, performance, and cost constraints. Research into new materials such as metal ceramic composites, improved resins, and engineered fibers is needed to meet cost targets without compromising performance. Materials to meet performance and cost requirements for hydrogen delivery and off-board storage are also needed (see Hydrogen Delivery section 3.2).

J. Lack of Tank Performance Data. An understanding of the fundamental mechanisms that govern composite tank operating cycle life and failure due to accident or to neglect is lacking. Data on tank performance and failure are needed to optimize tank structure for performance and cost. An independent test facility is needed that has the capability to acquire the required data.

K. Balance of Plant (BOP) Components. Light-weight, cost-effective, high-pressure balance-of-plant components are lacking. These include tubing, fittings, check valves, regulators, filters, relief and shut-off valves, and sensors.

Cryogenic Liquid Systems

L. Liquefaction Energy Penalty and Hydrogen Boil-Off. The boil-off of liquid hydrogen requires venting, reduces driving range and presents a potential safety/environmental hazard, particularly when the vehicle is in an enclosed environment. The energy penalty associated with liquefaction, typically 30% of the lower heating value of hydrogen, is an issue. Materials and methods to reduce boil-off in cryogenic tanks and to reduce the energy requirements for liquefaction are needed.

Reversible Solid-State Material Storage Systems (Regenerated On Board)

M. Hydrogen Capacity and Reversibility. Hydrogen capacity and reversibility are inadequate at practical operating temperatures and pressures and within refueling time constraints. Adequate cycle life of these systems has not been demonstrated.

N. Lack of Understanding of Hydrogen Physisorption and Chemisorption. Fundamental understanding of hydrogen physisorption and chemisorption processes is lacking. Improved understanding and optimization of absorption/desorption kinetics is needed to optimize hydrogen uptake and release capacity rates.

O. Test Protocols and Evaluation Facilities. Standard test protocols and independent facilities for evaluation of hydrogen storage materials are lacking.

P. Dispensing Technology. Requirements for dispensing hydrogen to and from the storage system have not been defined. This includes meeting heat rejection requirements during fueling.

Q. Thermal Management. Reversible materials typically require heat to release hydrogen on board. Heat must be provided to the storage system at reasonable temperatures to meet the flow rates needed by the vehicle powerplant. Similarly, while charging the material with hydrogen, a significant challenge is removal of the heat generated within the fueling time requirements.

Chemical Hydrogen Storage Systems (Typically Regenerated Off Board)

R. Regeneration Processes. Low-cost, energy-efficient regeneration processes have not been established. Full life-cycle analyses need to be performed to understand cost, efficiency and environmental impacts.

S. By-Product/Spent Material Removal. The refueling process is potentially complicated by removal of the byproduct and/or spent material. System designs must be developed to address this issue and the infrastructure requirements for off-board regeneration.

T. Heat Removal. Significant heat may be generated or required during formation of hydrogen, requiring substantial thermal management.

3.3.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.3.3. Issues regarding safety will be addressed within each of the tasks. The barriers associated with each task appear after the task title.

Table 3.3.3. Technical Task Descriptions

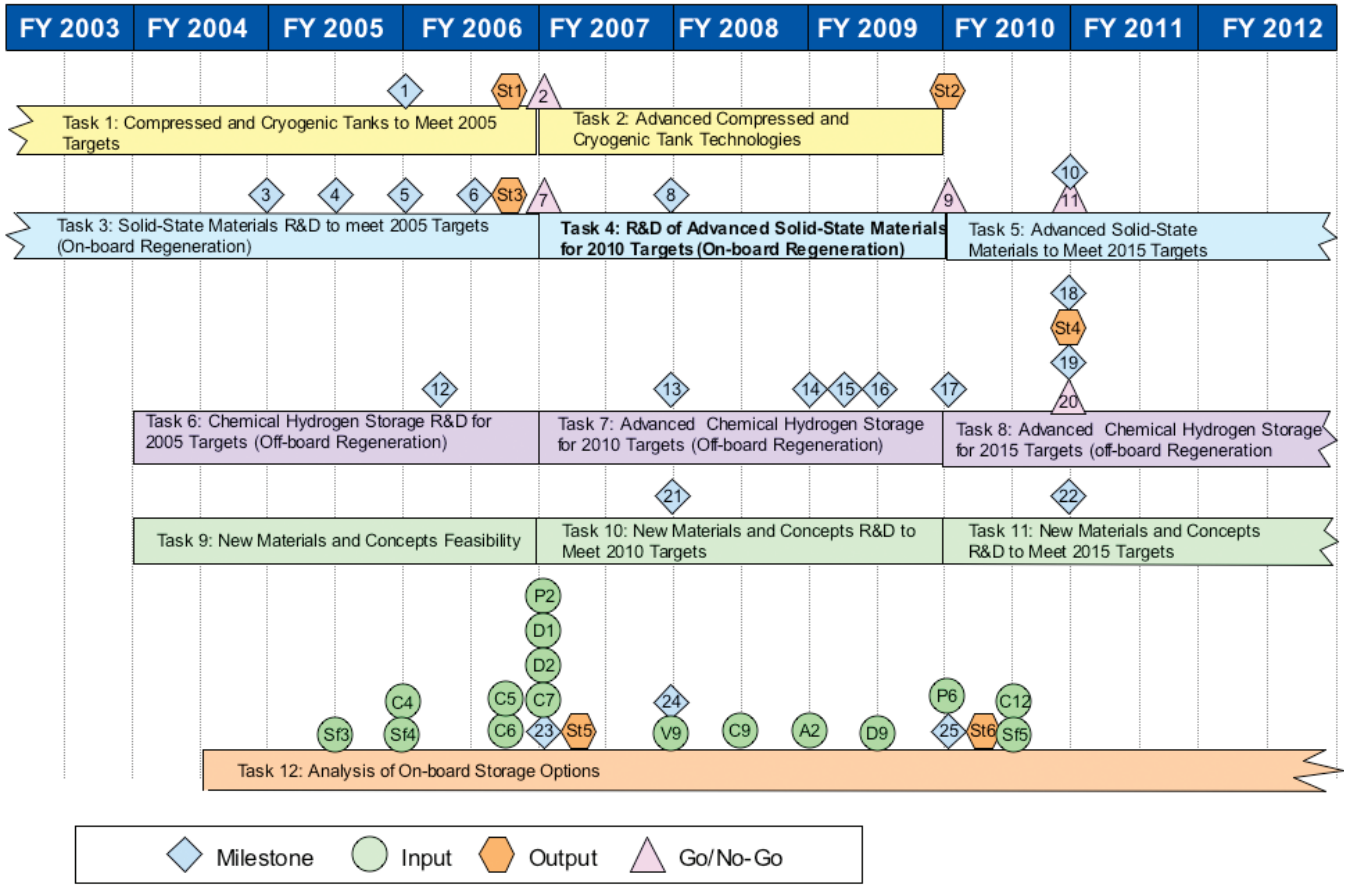
Task	Description	Barriers
1	**Compressed and Cryogenic Tanks to Meet 2005 Targets** • Develop, demonstrate and verify low cost, compact 10,000-psi storage tanks. • Assess the need for liner materials to reduce hydrogen gas permeation. • Develop and optimize carbon fiber/epoxy over-wrap. • Identify alternate designs and materials for advanced, integrated storage systems. • Explore conformable tanks for compressed hydrogen. • Demonstrate safety of hydrogen storage systems. • Explore compressed gas/reversible storage material hybrid systems. • Establish an independent test facility to acquire data on performance and durability of compressed tanks using standardized test methods. • Develop lightweight, low-cost balance of plant components for compressed and cryogenic tanks. • Study requirements and conceptual designs for cost-competitive off-board storage of hydrogen, including underground scenarios.	A-L
2	**Advanced Compressed and Cryogenic Tank Technologies** • Develop advanced compressed and cryogenic tank technologies to meet 2010 targets.	A-L
3	**Solid-State Hydrogen Storage Materials R&D to Meet 2005 Targets (On-board Regenerated)** • Perform theoretical modeling to provide guidance for materials development. • Improve understanding of sodium alanate system to aid development of alanate and other complex hydride materials with higher hydrogen capacities. • Investigate a family of alanate materials with hydrogen capacities of 6 wt% or greater with adequate charge/discharge kinetics and cycling characteristics. • Investigate composite-wall containers compatible with the optimal alanate materials. • Determine the decomposition products and pathways of materials to better understand their mechanisms and kinetics. • Engineer a hydride bed capable of efficiently storing and releasing hydrogen at 90°C. • Determine the hydrogen storage capacity of nanostructured carbon materials; demonstrate reproducibility of synthesis and capacity measurements. • Develop cost-effective fabrication processes for promising nanostructured carbon materials. • Explore combinatorial approaches to rapidly identify promising hydrogen storage materials. • Perform analyses to assess cost effectiveness of reversible hydrogen storage materials including scale-up to high-volume production. • Explore non-thermal discharging methods, including mechanical, chemical and electrical mechanisms. • Establish an independent test facility and standard test protocols to evaluate reversible hydrogen storage materials.	A-G, M-Q
4	**Advanced Solid-State Materials to Meet 2010 Targets (On-board Regeneration)** • Develop and verify most promising reversible storage materials to meet 2010 targets.	A-G, M-Q

5	**Advanced Solid-State Materials** • Develop and verify most promising reversible storage materials to meet 2015 targets.	A-G, M-Q
6	**Chemical Hydrogen Storage (Off-board Regeneration)** • Identify a family of chemical hydrogen storage materials capable of meeting weight and volume goals. Characterize the reaction chemistry and thermodynamics of the most promising candidates. • Rank viable candidates according to hydrogen capacity based on resource availability, full fuel cycle energy efficiency and emissions, and cost of the delivered fuel. • Identify and develop improved processes, chemistry, catalysts and operating conditions for the complete fuel cycle. • Evaluate the safety performance of the complete system. • Verify an entire closed loop, chemical hydrogen storage system, including an efficient regeneration process that meets cost and performance targets. • Ensure compatibility with applicable codes and standards for on-vehicle storage and fueling interface. • Assess the impact of a potentially complicated refueling process (due to spent material or by-product removal) on implementation of hydrogen storage systems that are regenerated off-board.	A-G, R, S
7	**Advanced Chemical Hydrogen Storage (Off-board Regeneration)** • Develop and verify most promising chemical hydrogen storage materials to meet 2010 targets.	A-G, R-T
8	**Advanced Chemical Hydrogen Storage (Off-board Regeneration)** • Develop and verify most promising chemical hydrogen storage materials to meet 2015 targets.	A-G, R-T
9	**New Materials and Concepts Feasibility** • Identify and investigate new materials and storage approaches that have the potential to achieve 2010 targets of 2 kWh/kg (6wt%) or greater, and 1.5 kWh/L or greater.	A-G
10	**New Materials and Concepts R&D** • Develop and characterize new materials and concepts to meet 2010 targets.	A-G
11	**New Materials and Advanced Concepts R&D** • Develop and characterize new materials and advanced concepts to meet 2015 targets.	A-G
12	**Analysis of On-board Storage Options** • Conduct analyses to examine life-cycle cost, energy efficiency, and environmental impacts of the technologies developed, changes in the system level requirements that might alter the technical targets, and progress of each technology development effort toward achieving the technical targets.	A-G

3.3.6 Milestones

Figure 3.3.4 shows the interrelationship of milestones, tasks, supporting inputs and outputs from other Program elements from FY 2004 through FY 2010. This information is also summarized in Table B.3 in Appendix B.

Figure 3.3.4. Hydrogen Storage R&D Milestone Chart



For chart details see next page.

Milestones

1 Complete feasibility study of hybrid tank concepts.
2 Go/No-Go: Decision on compressed and cryogenic tank technologies for on-board vehicular applications.
3 Complete construction of materials test facility.
4 Complete verification of test facility.
5 Reproducibly demonstrate 4wt% material capacity on carbon nanotubes.
6 Complete prototype complex hydride integrated system meeting 2005 targets.
7 Go/No-Go: Decision point on carbon nanotubes.
8 Down-select on-board reversible metal hydride materials.
9 Go/No-Go: Decision point on advanced carbon-based materials.
10 Complete prototype complex hydride integrated system meeting 2010 targets.
11 Go/No-Go: Decision on continuation of on-board reversible metal hydride R&D.
12 Complete preliminary estimates of efficiency for off-board regeneration.
13 Down-select from chemical hydrogen regeneration processes.
14 Demonstrate efficient chemical hydrogen regeneration laboratory process.
15 Complete chemical hydrogen storage life-cycle analyses.
16 Down-select from chemical hydrogen storage approaches for 2010 targets.
17 Complete prototype chemical hydrogen storage integrated system.
18 Demonstrate scaled-up chemical hydrogen regeneration process.
19 Identify advanced chemical hydrogen regeneration laboratory process with potential to meet 2015 targets.
20 Go/No-Go: Decision point on chemical storage R&D for 2015 targets.
21 Down-select from new material concepts to meet 2010 targets.
22 Down-select the most promising new material concepts for continued development.
23 Complete baseline analyses of on-board storage options for 2010 targets.
24 Update onboard storage targets.
25 Complete analyses of on-board storage options for 2010 and 2015 targets.

Outputs

St1 Output to Fuel Cells and Technology Validation: Compressed and cryogenic liquid storage tanks achieving 1.5 kWh/kg and 1.2 kWh/L.
St2 Output to Fuel Cells and Technology Validation: Advanced compressed/cryogenic tank technologies.
St3 Output to Fuel Cells and Technology Validation: Complex hydride integrated system achieving 1.5 kWh/kg and 1.2 kWh/L.
St4 Output to Delivery, Fuel Cells and Technology Validation: Full-cycle, integrated chemical hydrogen system meeting 2010 targets.
St5 Output to Delivery, Systems Analysis and Systems Integration: Baseline hydrogen on-board storage system analysis results including hydrogen quality needs and interface issues.
St6 Output to Delivery, Systems Analysis and Systems Integration: Finalon-board hydrogen storage system analysis results of cost and performance (including pressure, temp, etc) and down-select to a primary on-board storage system candidate.

Inputs

Sf3 Input from Safety: Safety requirements and protocols for refueling.
C4 Input from Codes and Standards: Standards for compressed gaseous on-board storage.
Sf4 Input from Safety: Safety requirements for on-board storage.
C5 Input from Codes and Standards: Hydrogen fuel quality standard as ISO Technical Specification.
C6 Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage tanks.
P2 Input from Production: Assessment of fuel contaminant composition.
D1 Input from Delivery: Assessment of cost and performance requirements for off-board storage systems.
D2 Input from Delivery: Hydrogen contaminant composition and issues.
C7 Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (CSA America).
V9 Input from Technology Validation: Final report on safety and O&M of three refueling stations.
C9 Input from Codes and Standards: Materials compatibility technical reference.
A2 Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.
D9 Input from Delivery: Off-board storage technology.
P6 Input from Production: Assessment of fuel contaminant composition.
C12 Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.
Sf5 Input from Safety: Safety requirements and protocols for refueling.